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"Array Beam Imaging" (ABI) software has been developed and tested using both radar and seismic wave fields for imaging based on backscattered (reflected) wave pulses from target objects. The ABI software is designed to produce high resolution target images showing internal structure of reflecting objects as well as external surface features. The images obtained are quantitatively proportional to the reflectivity (impedance contrasts) at target surfaces that produce reflections of incident waves. Therefore, reflectivity images using seismic and electromagnetic waves produce sets of images that measure quite different physical properties of the targets. These independent images can be compared (correlated) with the corresponding images of standard mine types for identification purposes using external and internal boundary shapes and other special reflectivity differences between mines and miscellaneous clutter.

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Array Beam Imaging for High Resolution Stand-Off Mine Detection
SBIR Contract: DAAB07-97-C-G009
Final Report, June 11, 1997

Project Description and Technical Objectives

We propose to demonstrate the feasibility of a sensor/data fusion imaging system which combines existing seismic and radar array technology with the use of novel image processing software. The proposed Array Beam Imaging (ABI) system will be designed to produce high-resolution 3-D tomographic images of surface and buried objects in a variety of soil conditions; particularly in the presence of ground clutter and extraneous targets.

The study will pursue the following technical objectives in order to determine the practical feasibility of the ABI mine detection system:

- Investigate ultra-high frequency seismic wave propagation over distances of several meters in earth media likely to be encountered in mine detection applications.
- Determine, through computer simulations, optimal seismic source and receiver array configurations for seismic imaging.
- Demonstrate the capability of imaging shallow buried land mines with the ABI software and an array of seismic sources and receivers, and with radar arrays.

  Assess the added performance capabilities produced by combining radar data sets with seismic data sets in the ABI imaging system.

Summary of Previous Work

In the five previous reporting periods major research results included:

(1) Adaptation of the 3-D seismic modeling program for generation of very high frequency wave field predictions in complex solid media comparable to a rocky soil and/or sand environments near

the earth's surface. This work was successfully completed and initial applications designed to optimize seismic sensor array designs and source distributions for stand-off mine detection were begun.

(2) Observational studies using new seismic source designs to quantitatively investigate seismic wave propagation characteristics in near surface soils, under varying moisture conditions, were successfully conducted. Absorption characteristics in moist soil were quantitatively determined and indicate efficient ultra-high frequency (in the range up to 5 to 10 khz) seismic wave propagation in soils with higher water content, with *decreasing* absorption with increasing frequency. This result indicates that seismic reflection tomography will be most powerful for detection and imaging in moist or saturated soil environments and therefore an ideal complement to radar which is most effective in dry, water free conditions.

(3) The ABI imaging methods were applied to ground penetrating radar data from test sites in Europe. Buried objects, including metal and plastic pipes of varying dimensions, where successfully imaged in "photographic" detail at depths near and below 1 meter. Significantly, the processing was carried out on a PC computer at speeds near real-time, indicating capability for very rapid detection and identification of objects at considerable depth with a field deployable combined source, receiver and processing system.

(4) Tomographic imaging of synthetic seismic data (computer generated wave fields) using very high frequency (several kilohertz) seismic waves from buried objects shows near real-time imaging of objects that is similar, in object image detail, to radar imaging in the 2 gegahertz range. In particular, object detection and identification can be expected at near real-time with PC computer system processing. Current optimization studies of desirable source/receiver characteristics and array configurations using synthetic seismic data have provided results that will be used in subsequent experimental tests at field sites under typical noise and clutter conditions.

(5) We have continued to develop and test radar imaging using data supplied by several U.S. and foreign companies engaged in GPR hardware development. The test sites used contained metal and plastic objects buried at various depths (down to about 2 meters) in soils and sands with differing moisture content. The radar data obtained provide good, controlled, tests of detection and imaging capability. Our imaging results have been impressive so far. The radar images obtained are often of near photographic quality and in all cases result in quite accurate images of buried test object shapes, and provide, from tomographic sections, accurate details of the internal structure of the object. An important consequence of the high resolution of object shapes, at one meter and shallower depths, is the ability to obtain separate and accurate images of closely spaced objects without wave interference between objects distorting and obscuring individual images. This indicates that target objects of interest can be detected, and usually identified by shape and internal structure, even in the presence of rather dense clutter by using ABI signal recording and processing.

(6) ABI imaging using standard GPR equipment and field procedures at a Swiss test site produced reasonable shape accuracy and, as well, imaging of internal structure of plastic mines with both external shape and internal structure allowing identification. It is particularly important that these ABI images were obtained in near real-time from processing of the data using a low cost PC computer. Thus, because of the processing speed and the low cost computer hardware, as well as the accuracy and clarity of the images, the radar source-sensor system and the computer system could be combined in one field unit for practical portable field use, and with expectations of accurate identifications by non-specialist personnel.

(7) The hardware components of the seismic sensor/transmitter array system were designed and extensively tested. The components included a small sized seismic pulse generator that produces linear coupling in soil environments and therefore allows signal stacking and is capable of producing ultra broad-band pulses, with high energy in the 10 kHz range. Microphone detectors, preamplifiers and detector enclosures of compact field deployable design were assembled and

extensively tested in an array configuration, along with a digital acquisition system for the array. A finalized sensor and digital recording system was successfully produced for stand-off seismic array processing and imaging and the array assembly is being tested under field conditions.

(8) Extensive blind imaging tests using a Micropowered Impulse Radar (MIR) synthetic array system was conducted using data from a company in Japan. Successful imaging of rebar in concrete, using large block samples from bridges in Japan, were carried out. The results indicate that a MIR transmitter/receiver array would be effective in real-time imaging of buried objects, such as land mines and unexploded ordnance, in field applications involving small, light weight, portable or hand-held array units positioned above the target zone.

(9) Further land mine detection tests were performed using radar data obtained at special test sites by radar equipment manufacturing companies seeking to test their equipment. The test data was obtained using standard profiling techniques. Land mines of various types buried at shallow depths were imaged successfully. The processing produced accurately located images of the mines showing external shapes and internal properties with sufficient detail to allow visual identification of the detected objects.

(10) A seismic array composed of detectors developed under this program was designed and tested. The impulse source developed was also used in these tests and signals recorded across the array were found to have wave forms that changed only slowly across the detector array and, in addition, contained signal power above noise levels in the frequency band from .5 kHz up to 6 to 7 kilo-hertz for signal propagation distances up to several meters. These results show a potential for stand-off detection capability out to 2-3 meters using low power seismic sources and receiver arrays.

Activities in the Current Monthly Reporting Period

The Principal Investigator visited the US Army Night Vision Directorate at Fort Belvoir, Virginia and presented a summary of the current status of the Phase I program and discussed plans for a

Phase II program. A summary of some principal results of Phase I and planned developments for Phase II, as presented at the meeting, are included as an attachment to this report.

Testing of seismic arrays and sources were continued during this reporting period. In addition, computer simulations of seismic wave propagation in different heterogeneous media types were generated in order to evaluate seismic imaging as a function of detector and source array configuration for variable media conditions. Both activities are on-going and will be continued during the Phase I - II interim period.

Major Results and Conclusions

Figure 1 shows an example of the seismic wave fields predicted by 3-D computer wave field modeling. This capability along with actual field test data is being used to perfect seismic imaging of objects at very shallow depths, such as is normally the situation for land mine detection.

Figure 2 illustrates results from the computer simulation tests of seismic array recording in complex soil-like media. Analysis of this data, and similar results in media with less clutter than this particular example, indicates that a large surface wave (a Rayleigh type fundamental mode surface wave) is generated by the near surface seismic source and is the largest signal propagated at shallow depth into the target zone. This wave therefore produces back scattering from shallow buried objects that is recorded by the stand-off array. The principal reflected wave that is recorded by the array is also in the form of a surface wave. The imaging of these wave types to define reflecting/scattering objects requires a somewhat different approach than previous imaging methods (such as with stand-off radar data, or with seismic imaging of deeply buried objects using reflections from simple direct waves) and we are modifying the imaging software system accordingly.

Compressional Wave Field

Shear Wave Field

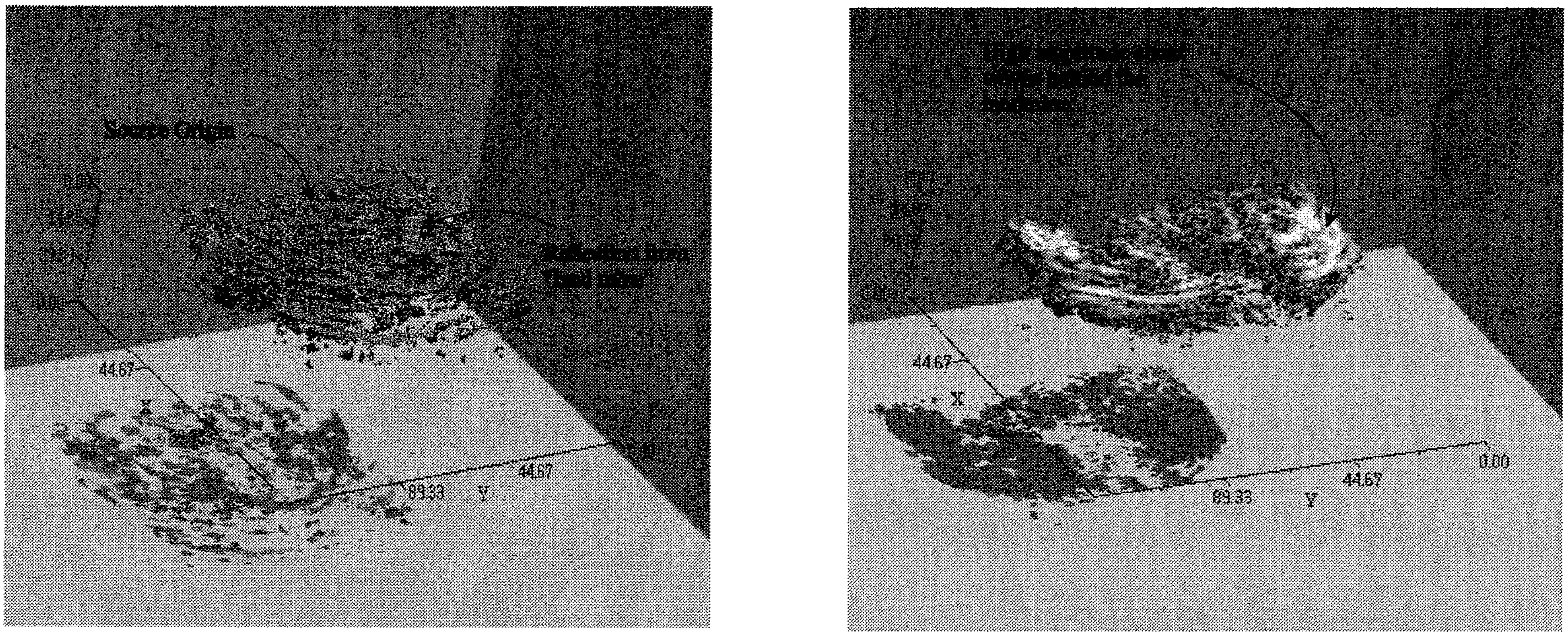

Figure 1. Snapshots from a computer-generated seismic wave field in a highly varied model of shallow soil. The volume of the region modelled is about 2 meters by 2 meters by 60 cm. The snapshots were recorded 12.5 milliseconds after firing of an impulsive point source oriented with its force vector along the positive x-axis and located towards one end of the "test pit", as shown in the figure. The source was located 10 cm beneath the soil surface and contained frequencies up to about 3 kHz. The presence of a landmine in the soil was simulated by including a disk-shaped region of material with a seismic wave velocity contrast of about 6:1 relative to the surrounding medium The landmine was placed 10 cm beneath the surface and had a diameter of 12 cm. Reflections from the landmine are clearly visible. The orange color of the shear wave field versus the green of the compressional field represents the much higher amplitudes of the shear waves versus the compressional waves generated from the near-surface vector point source. The dominant outgoing signals in the wave field are the surface waves incident on and reflected from the landmine, while the dominant reflected signal is a compressional wave reflected from the mine.

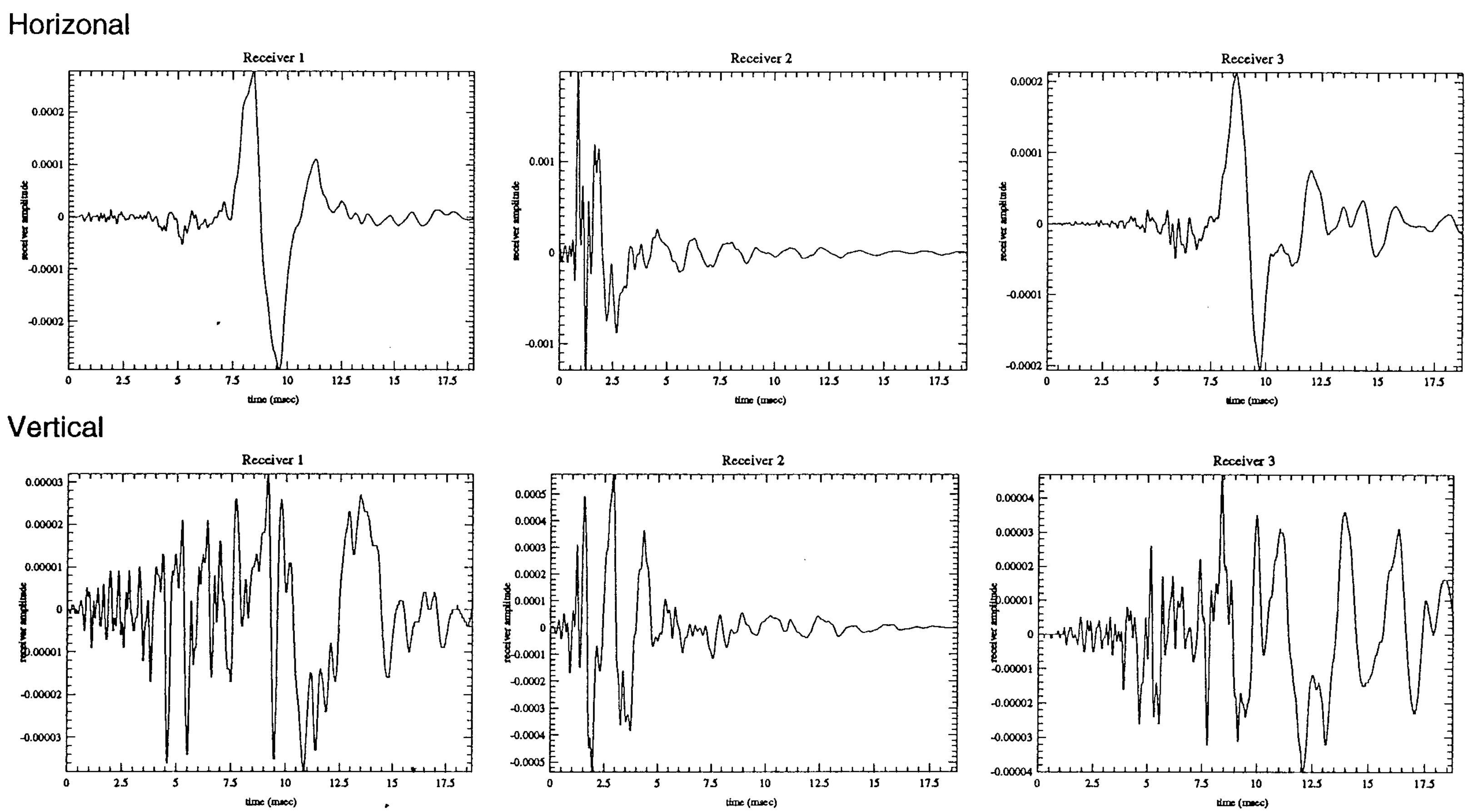

Figure 2 - Time series recorded on the soil surface for the computer simulation of Figure 1. The time series on the top row are a component of horizontal particle motion, while the series on the bottom are of the vertical component of particle motion. The three receivers are rougly symmetric about the source, with Receiver 2 directly in front of the source and Receivers 1 and 3 in front of the source and towards either side of Receiver 2. The highest amplitude signal in the series is a surface wave. Complications in the wave field develop quickly from the high degree of random fluctuations (20% rms) in the material properties. Later arrivals in the time series are of lower frequency than the earlier arrivals due to the high absorption of the material (Q = 50 for the compressional waves).

Final Summary Report on Work Accomplished in Phase I and Plans for Interm and Phase II Programs

I. Results, Uses and Present Status of Mine Detection System Development

(1) "Array Beam Imaging" (ABI) software, version 1.0, has been completed and tested using both radar and seismic wave fields for imaging based on backscatttered (reflected) wave pulses from target objects. The ABI software is designed to produce high resolution target images showing internal structure of reflecting objects as well as external surface features. The images obtained are quantitatively proportional to the reflectivity (impedance contrasts) at target surfaces that produce reflections of incident waves. Therefore, reflectivity images using seismic and electromagnetic waves produce sets of images that measure quite different physical properties of the targets. These independent images can be compared (correlated) with the corresponding images of standard mine types for identification purposes using external and internal boundary shapes and other special reflectivity differences between mines and miscellaneous clutter.

The important features of the software imaging system for Army applications includes:

- Capability for very accurate, high resolution, imaging using backscattered wave pulses recorded with arrays of sensors. This capability is important for identification of mines (or other targets of interest) in high clutter zones.

- The imaging software has wide applicability in that wave fields that can be used include electromagnetic waves, in various frequency ranges (infra-red, radar, x-ray, etc.), and mechanical waves in solids, fluids and gases (seismic/elastic, acoustic). This software can therefore be used with other existing sensor systems, such as with sonar, infra-red or x-ray receivers, to produce images useful in a variety of applications in addition to mine detection.

- The imaging technology has been implemented on small computers (workstations and personal computers) and is computationally fast, producing detailed 3-D images of small targets in scan zones of a few cubic meters in compute times of tens of seconds using a 133 MHz PC. These imaging rates can be reduced significantly if the new faster low cost hardware systems are used. Such speed will allow "real-time" imaging that can be usefully applied, particularly when mobile land or airborne sensor platforms are used.

- In addition to 3-D images that may be generated from backscattered (reflected) wave fields (which may be described as products of "reflection tomography") the ABI imaging method, and the current software, can be applied to primary fields generated by natural or man-made sources of wave fields to produce 3-D

- Images defining the shapes and spatial locations of wave field emitters. Therefore the imaging software may be used to perform "emission tomography" as well as "reflection tomography", which allows, for example, imaging of abundant and militarily important sources of infra-red radiation. (Army applications could include the use of this imaging technology for tracking and identification of heat radiating

objects under low visibility conditions.) Emission and reflection tomography (and associated imaging) can be performed simultaneously with the same hardware-software system, so that independent modes of functionality are available which produce images of both "emitters" and "reflectors". Simultaneous use of both kinds of images would clearly allow better identification of different kinds of targets and their physical characteristics.

(2) The basic hardware components for seismic imaging have been produced and tested for use in a Seismic Array Imaging (SAI) system. The basic elements of the SAI system include a miniaturized seismic impulse source with a band width spanning the 1 to 10 kHz range and a miniaturized electret sensor element mounted on a preamp electronics module. The sensor element has the desired linearity, sensitivity, uniform response and small size (6 mm by 5 mm) to make it appropriate for use in a multi-sensor array configuration in which each sensor is housed in a cylindrically shaped metal casing, designed for ground penetration and good coupling of the sensor element to the medium. The ground penetrating sensor element, with its cylindrical housing, is 8.5 mm in diameter and 50 mm in length (Figure 1), but can be reduced in size.

The source element produces repeated, low power, broad band impulses by simple impact of a metal plunger against a small metal plate in contact with the medium. As shown in Figure 2, plate orientations parallel or normal to the ground surface can be used, with a vertical orientation usually used. The source mechanism is housed in a cylindrical ground penetrating casing, illustrated in Figure (2), which is about 70 mm long and approximately 25 mm in diameter. The impact plate is placed at, or near, the bottom end of the casing to insure good coupling to the medium. (Water injection and medium wetting at the contact plate can be used to enhance seismic coupling to the ground.)

Tests involving these hardware elements, with a digital acquisition system for array operation, have provided the following results:

- The low power, pulsed seismic source design results in linear coupling to the medium and produces repeatable impulsive signals that allows repeated source excitation and receiver time-series "stacking", which greatly enhances reflected signal levels relative to random background noise.

- Tests have demonstrated that pulse reflections from targets in the 2 to 3 meter distance range in typical damp near surface soils have spectral amplitude levels well above noise out to 5-10 kHz, when simple "stacking" is used along with multi-receiver array processing. (This performance can be enhanced with higher source pulse repetition rates and longer periods of source pulsing and stacking.) Wave lengths associated with the high frequency pulses are in the 5-10 cm range, which can produce resolution capability at the 1 to 2 cm level when multi-receiver arrays are used. Such resolution will provide mine identification in clutter, in most circumstances.

- Tests of seismic wave propagation under varying soil conditions have shown high signal to noise levels in the 2-3 meter distance range and a reduction in attenuation with increasing frequency in the 1-10 kHz band in damp/wet soils. Therefore, high resolution imaging, using short wave length (5 cm or less) seismic reflections, is much enhanced in wet or damp media. Greater depth imaging is also possible; to depths of 1 to 2 meters. This indicates high detection capability in

DETECTOR ASSEMBLY

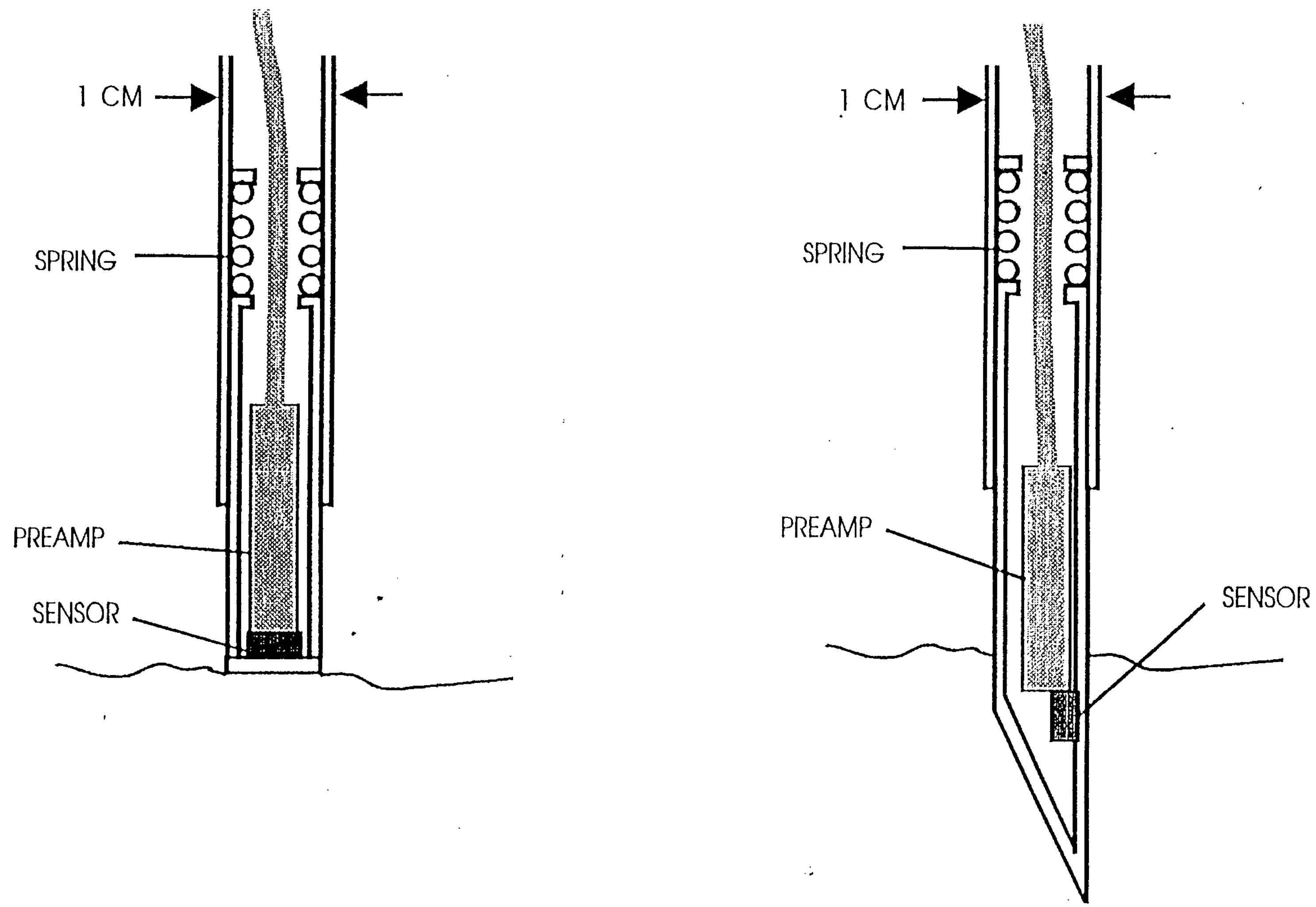

Figure 1. High frequency seismic detectors in two configurations. The ground penetrating version on the right has been successfully fabricated and tested.

IMPULSE GENERATOR

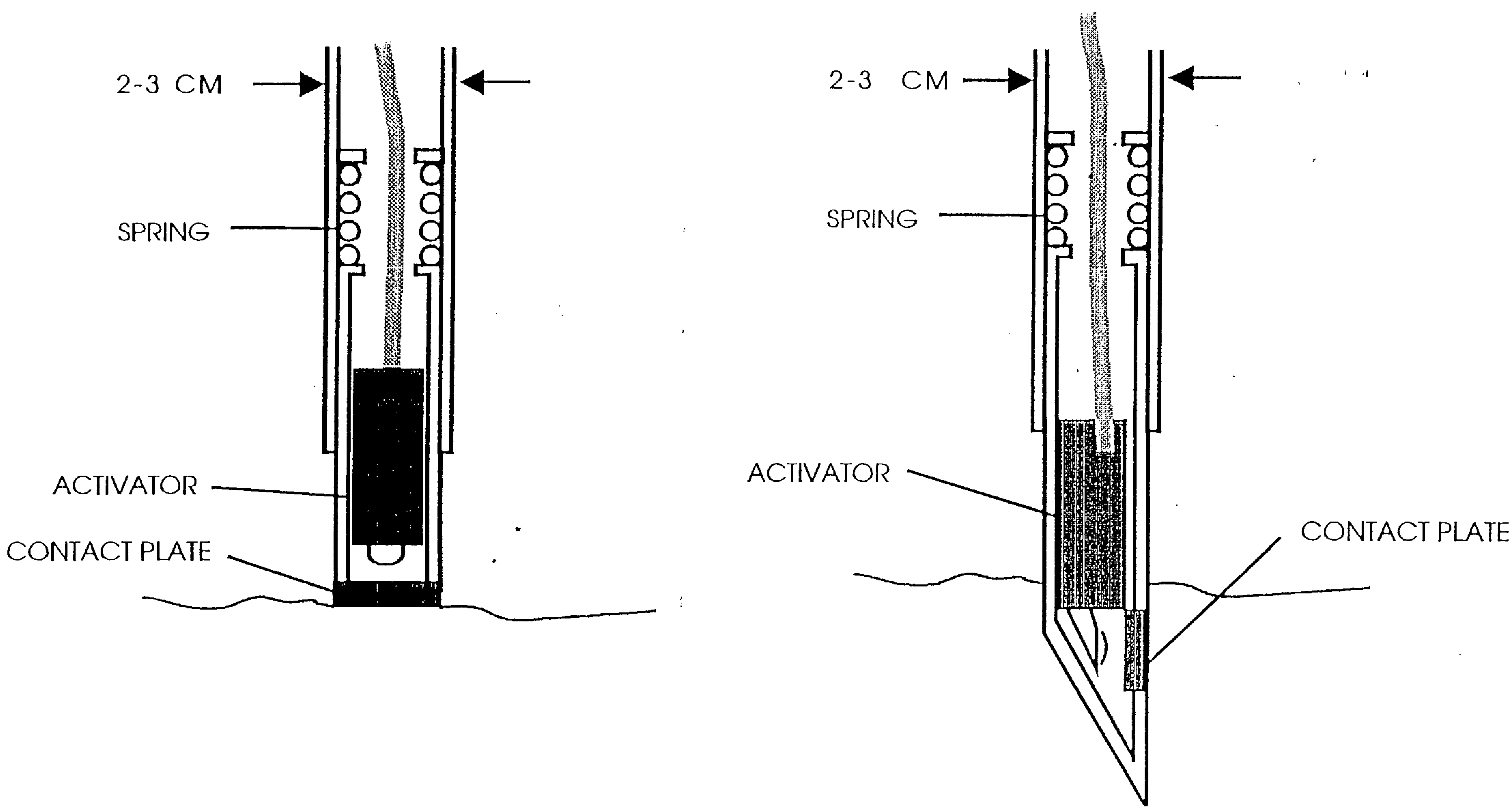

Figure 2. Seismic broad-band generator designs, for high frequency (1-10 kHz) repeatable pulse generation. The ground penetrating design on the right has been successfully tested in prototype form.

shore line and swamp areas where other methods, such as radar, may loose efficiency.

These field tests, along with computer based simulations and applications of array beam imaging methods, have demonstrated that seismic imaging using the designed source and receiver elements is certainly feasible. Further, it is clear that seismic imaging can have considerable value, when used together with pulsed radar, in extending the range of detection capability from dry to wet environments, extending detections to greater depth and enhancing the ability of a dual system to identify mine targets in high clutter environments.

(3) Ground penetrating radar (GPR) data, from both standard commercial systems and the Micropower Impulse Radar (MIR) designed at Livermore Laboratories, has been processed with the ABI software in synthetic array imaging tests. Buried land mines, as well as a variety of other targets, have been imaged using the ABI software. High resolution images of mines, pipes and metal rebar in soil, sands and concrete have been obtained and show accurate details of outer surface shapes and internal boundaries within the targets. All tests used one dimensional profile data, rather than true two dimensional surface array data, and with the data obtained by second parties at controlled test sites.

The important results for mine detection applications are:

- Close spaced profiling with standard pulsed GPR produced accurate 3-D images of small diameter metal and plastic pipes in close proximity to each other, in some cases with barriers between targets and receivers (i.e. high clutter conditions). The results indicate high level detection and imaging capability to depths in the .5 m to 1 m range for small targets when close spaced receiver array configurations are used; particularly when true, two dimensional receiver arrays positioned above the target zone are used.

- Tomographic sections through mines showed internal reflectivity boundaries that were sharply defined. Such internal structure imaging, along with 3-D external surface images, should allow mine identification by operator or computer automated pattern recognition with high confidence.

- The transmitter and receiver components of existing ground penetrating radar systems are small and easily configured in radar arrays. The low power MIR element, for example, is 5 cm x 10 cm x 10 cm and weight only a few ounces. (Smaller versions are also possible.) A circular array panel with 10 to 20 such elements would be appropriate as a scanning array and would be only about 25 cm in radius.

II. Planned Developments and Expected Results Under the Proposed Phase II Program.

(1) Array Beam Imaging methods can be considerably expanded and refined under a phase II development program. The objectives of the planned extensions of this technology are to produce more accurate and detailed 3-D images through noise and interfering signal rejection techniques in high noise, high clutter environments. In particular, performance can be improved considerably in cases when signal levels are quite low relative to noise and when multiple reflectors, in close proximity, produce wave interference effects that obscure secondary reflector images or produce false images. The methods that we will implement to expand the ABI performance include the following:

- Auto-focusing algorithms to produce proper array element phasing.

- Polarization pre-filtering of the wave fields to reject noise of differing wave type and interfering signals from outside the array beam solid angle. This filtering will reduce or nearly eliminate interference and image distortion.

- Multiple narrow band filtering and array auto-focusing will be introduced to properly process strongly dispersed signals, which have different propagation velocities in different frequency bands, in order to enhance imaging of reflector shapes.

- Use of iterative image decomposition methods, involving subtraction of strong reflector signals from raw data, will be introduced to allow imaging of hidden or obscured reflecting objects in clutter.

- Sequential source illumination and imaging of reflectors in the target area using a spatially distributed source array will be added. The subsequent superposition of these independent reflector images will produce "compound" target images, incorporating wide angle illumination and more complete target illumination with much superior images, particularly under high clutter conditions.

These ABI enhancements should provide more optimal detection of land mine targets with both the seismic and radar systems. Automated image correlations between candidate mine characteristics and the high resolution images produced by the enhanced ABI processing would also be developed as an aid to operator identifications of probable land mines. The capabilities of the ABI processing system will be evaluated for a variety of imaging applications, as well as for land mine detection purposes.

(2) The seismic array configuration will be developed using refined versions of the sensor-transmitter elements designed during the Phase I program. The array will be designed to include independent source and receiver arrays within the same array panel in order to incorporate distributed source illumination of target reflections. Figure 3 indicates the geometry and size of the panels to be produced and tested.

The seismic array will consist of a rectangular distribution of sensors arranged in several rows and each separated by about 10 cm. The sensor casing will be rigidly attached to the panel so that fixed positions will be maintained. The sensor is to be fabricated with spring loading and would normally be designed for ground penetration, as indicated in Figure 1. A single line of sources, distributed from end to end along the mid-line of the panel will provide the primary wave fields that are propagated forward into the volume to be scanned for reflector targets. Back-scattered secondary waves from the targets are recorded at the sensors and used for imaging. Figure 4 schematically illustrates a vehicle-mounted seismic array system used to scan a forward target area, as it might be configured in an actual field system.

In addition to the sensor-transmitter array, a data acquisition system will be used to transfer digital data to a small computer system which performs on-line ABI processing and provides screen display of reflector images, both in three dimensional perspective and as tomographic sections. This part of the SAI hardware system is already available commercially, with only minor modifications required for particular application to the SAI.

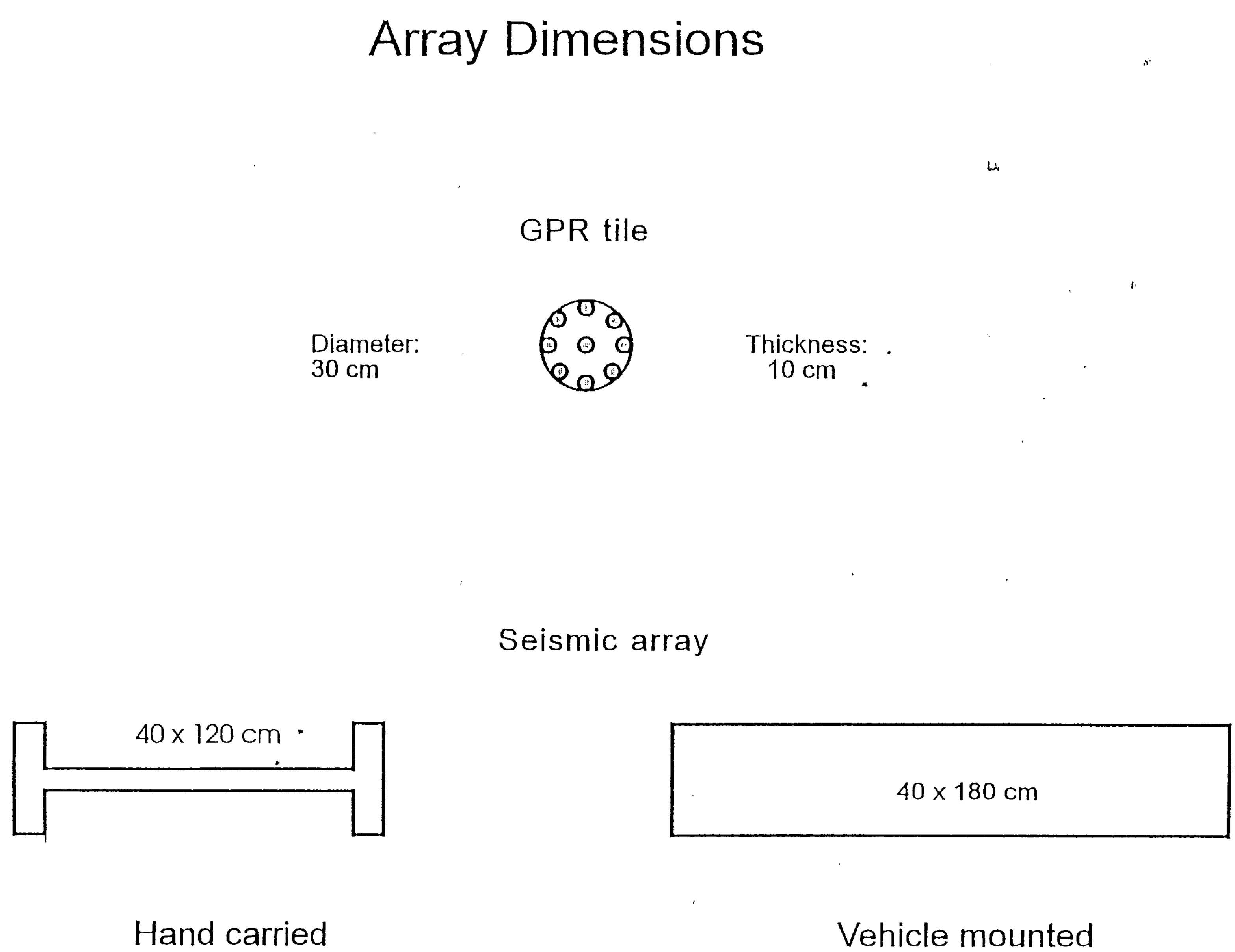

Figure 3. Radar and seismic array panel configurations.

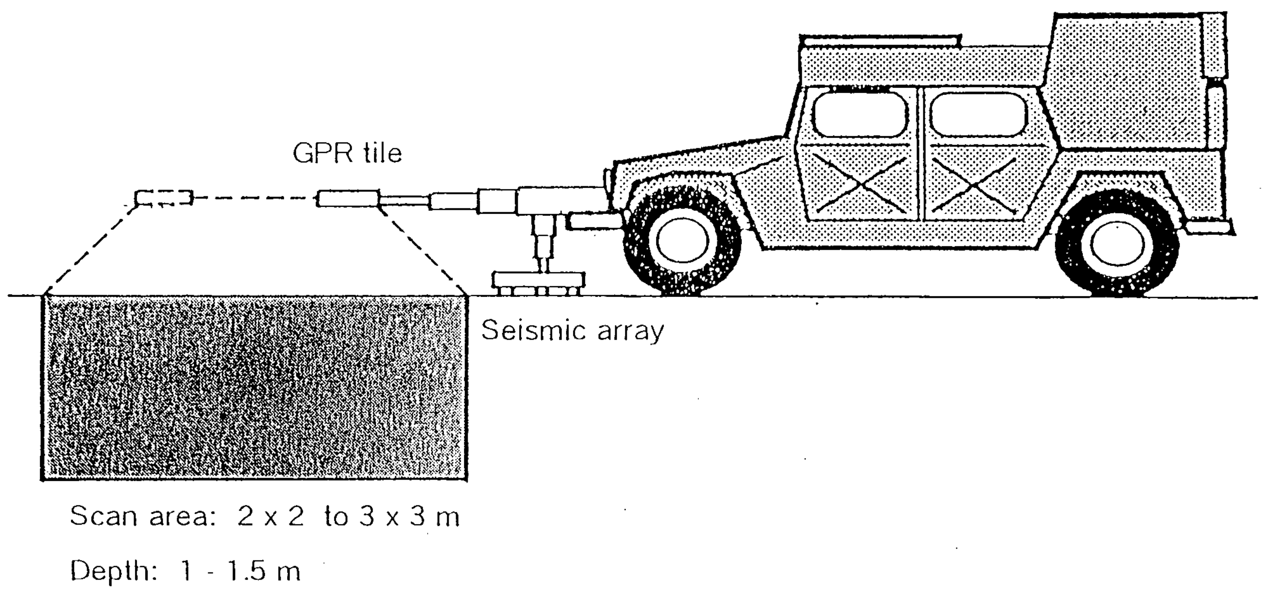

Figure 4. Schematic of vehicle mounted scanning arrays for dual seismic and radar mine detection. Smaller versions can be designed for hand-held or small robotic platforms.

The principal tasks and objectives of the part of the Phase II program involving this seismic system are therefore:

- To fabricate a seismic sensor-transmitter array of the type described and to test and evaluate its performance as a component of a Seismic Array Imaging (SAI) system.

- To refine and improve the design of the array elements and the array configuration as required to achieve high levels of detection and imaging capability.

- To combine the SAI system with the Radar Array Imaging (RAI) system for dual field detection/identification of land mines in high clutter environments.

(3) Radar array elements are available commercially and will be acquired on loan, or with a lease agreement, through one or two of several possible sources. Configuration in a suitable array geometry can be carried out relatively simply, since a small movable array, like that indicated in Figure 3, is planned. This array would be positioned above the scan area as illustrated in Figure 4, or mounted on a hover craft or helicopter, and could be rapidly moved to scan the target area in sections. The receiver and transmitter in the radar elements are coincident in the small radar units to be used, so the array will be both a source and a receiver array. Again, digital acquisition systems and the small computer system required are commercially available and will provide on-line imaging using ABI processing.

The principal tasks and objectives involving the development of a Radar Array Imaging system are:

- To fabricate the radar array using the small radar receiver-transmitters available and to test and evaluate its performance.

- To refine and improve the array design as required.

- To combine the RAI system with the seismic system imaging results to provide dual field detection/identification of mines in high clutter environments.

(4) At the end of a Phase II program, we would expect to have accomplished the following:

- Development of next generation seismic array hardware and its array configuration.

- Selection and adaptation of GPR hardware and its array configuration.

- Extension and optimization of both seismic and GPR imaging software.

- Incorporation of special software/display features, such as data quality indication, pattern recognition and correlation, etc.

- Integration of seismic and GPR subsystems into a data fusion mode.

- Construction of a demonstration prototype, using leased GPR equipment, suitable for field demonstration of the ABI system.

- Conceptual design of the final versions of ruggedized, field deployable ABI systems, for one or more operational modes.

- Arrangements for initial production and commercialization.

We intend to move this development forward and to reach the beta test and commercial production stage as quickly as possible. To this end, wherever possible we would extend the work into Phase III activities as we perform the Phase II work.